Effects of Object Size on Intralimb and Interlimb Coordination During a Bimanual Prehension Task in Patients With Left Cerebral Vascular Accidents

Ching-yi Wu, Shih-han Chou, Mei-ying Kuo, Chiung-ling Chen, Tung-wu Lu, and Yang-chieh Fu

Stroke patients are often left with hemiplegia or hemiparesis of the upper extremities, severely limiting the ability to perform bimanual and functional activities. No studies have investigated how stroke patients adapt their movements to changes in object size in functionally asymmetric bimanual tasks. The influence of object size on intralimb and interlimb coordination during an asymmetrical, functional bimanual task was examined in patients with left cerebral vascular accidents (LCVA) and healthy controls. Fourteen LCVA patients and 13 age-matched controls were instructed to reach to grasp a large and a small jar with the right/affected hand and to open the cap with the other hand. Movement kinematics was analyzed for intralimb coordination (spatial and temporal planning of reaching and grasping) and interlimb coordination (bimanual synchronization and temporal association of the hands). The results demonstrate a spatial adaptation of reaching in the affected hand to the object size and deficits in temporal planning of grasping with the affected hand to object size in the stroke patients. Movement adaptations of the unaffected hand in the stroke patients were similar to those in the healthy adults. Bimanual coordination was independent of object size for both groups.

Keywords: object size, bimanual coordination, stroke, reach to grasp

Object properties such as object size are viewed as constraints and are evidenced by channeling changes in the performance of the upper extremities (Säfström & Edin, 2005; Shumway-Cook & Woollacott, 2001). According to Jeannerod’s visuomotor channel model, object size (i.e., intrinsic properties of objects) influences the patterns of the goal-directed reach-to-grasp (i.e., prehension) movement (Jeannerod, 1999). Most studies (Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Cope & Trombly, 1998; Jeannerod, 1999; Kudoh, Hattori, Numata, & Maruyama, 2005) investigated the effects of object size on movement parameters in healthy adults. However, a systematic study on bimanual coordination in patients with LCVA is still lacking.
Object Size and Bimanual Task

1997; Marteniuk, Leavitt, MacKenzie, & Athemes, 1990; Mon-Williams & Tresilian, 2001; Zoia et al., 2006) investigating the influences of object size in healthy adults and children with cerebral palsy have focused on its impacts in unimanual movements. No studies have looked at how stroke patients adapt the movements to the change of object size in functionally asymmetric bimanual tasks. Stroke patients often have accompanying hemiplegia or hemiparesis of the upper extremities, severely limiting the ability to perform daily tasks requiring both hands (Messier, Bourbonnais, Desrosiers, & Roy, 2006). Understanding the performance of intralimb and interlimb coordination in response to object size in stroke patients might provide insight into the underlying control processes and would help shape treatment strategies for rehabilitation (Carr & Shepherd, 2003; Volman, 2005).

A unimanual prehension movement consists of two components: a reach component, which is based on visual analysis of the object’s spatial properties to transfer the arm to the location of the object, and a grasp component, in which the hand is preshaped and formed based on the visual information of the object’s intrinsic properties to allow it to be successfully gripped. These two components are proposed to be controlled via separate but interacting visuomotor channels (Jeannerod, 1999; Marteniuk et al., 1990). The size of the object is assumed to be mainly analyzed via the grasping channel and directly affects the grasp performance (Säfström & Edin, 2005). A few studies (Marteniuk et al., 1990; Zoia et al., 2006) found object size also influenced the reaching phase. When the size of the object decreases, the requirements of spatial precision for reaching and grasping increase; the individual moves more slowly and indirectly and spends more time in the deceleration phase of reach for on-line error correction (Bootsma et al., 1994; Kudoh et al., 1997; Marteniuk et al., 1990; Zoia et al., 2006). The individual also tends to achieve a maximum grip aperture (MGA) earlier during the reach to a smaller object to more precisely tailor the hand shape to the object size during the later phases of the reach (Cope & Trombly, 1998). Furthermore, a smaller MGA is needed for the smaller size (Jeannerod, 1999; Mon-Williams & Tresilian, 2001).

The prehension movement is not limited to unilateral movement; it is also performed bimanually. In many everyday tasks, such as opening a jar, both the arms and hands operate together to adapt their movement so as to achieve the particular goals (Kazennikov, Perrig, & Wiesendanger, 2002; Volman, 2005). Such functional and asymmetrical bimanual tasks are seldom studied and hence are only poorly understood (Obhi, 2004). The asymmetric bimanual movements include intralimb performance and interlimb coordination. The kinematics of intralimb performance has been analyzed for the purpose of understanding unilateral behaviors during functional bimanual tasks (Serrien & Wiesendanger, 2000). Whether the control mechanisms of each hand in response to object size during bimanual movement are similar to those during unimanual movement, and whether they can be also explained by the visuomotor channel model, is a subject requiring investigation.

For interlimb coordination, the kinematic characteristics during bimanual movements are well established. Interlimb coordination emphasizes the goal-directed temporal invariance of both hands. The two hands are well synchronized and highly correlated at both the end of the movement as well as at the initiation of the movement (Kazennikov et al., 2002; Weiss, Jeannerod, Paulignan, & Freund, 2000; Wiesendanger, Kaluzny, Kazennikov, Plmeri, & Perrig, 1994). It is suggested that there is a common temporal mechanism, in a higher-order control
system, organizing the separated channels of the two arms and hands into a single unit for synchronization at the goal (Jackson, Jackson, & Kritikos, 1999; Serrien & Wiesendanger, 2000). The principle of temporal synchronization has been shown to be independent of the specific task constraints (e.g., loading on one hand, visual occlusion, and speed emphasis), primarily in healthy adults (Perrig, Kazennikov, & Wiesendanger, 1999). In contrast, Utley, Steenbergen, and Sugden (2004) suggested that bimanually grasping a small object resulted in better bimanual coordination than grasping a large one in children with cerebral palsy.

Recent studies have indicated that the left hemisphere is particularly important for the programming and integration of unilateral and bilateral reach-to-grasp movements. Patients with left hemisphere lesions exhibit deficits in intralimb trajectory control (Haaland, Prestopnik, Knight, & Lee, 2004) and interlimb synchronization of movement trajectories for symmetrical movements (Serrien, Nirkko, Lövblad, & Wiesendanger, 2001). Knowledge of the kinematic modifiability of the performance of persons with and without left cerebral vascular accidents (LCVA) on object size during bimanual prehension movement might provide important information about how stroke patients can learn to perform daily activities more effectively and help the development of efficient intervention strategies for regaining motor function that has been compromised (Messier et al., 2006).

Given the lack of data on bimanual coordination in response to object size during a functionally asymmetric bimanual task in healthy adults and patients with LCVA, the purpose of this study was to obtain such evidence. Performance of the healthy adults was studied to provide a basis on which to establish normal patterns in task performance. A functional task (i.e., reach and grasp a jar and move the jar on the work position with one hand, and unscrew the jar cap with the other hand) was used to directly reflect patients’ performance demands in daily life. We hypothesized that the intralimb performance (i.e., reach-and-grasp component) would be different under different size conditions for both groups. When reaching to grasp a smaller jar with one hand and reaching to grasp to open a smaller jar cap with the other hand, participants in both groups were expected to move more slowly with less direct movements, generating a smaller aperture; to require more time in the deceleration phase of reach; and to achieve MGA earlier. For moving a jar to the work position, no differences in movement performance between two sizes of the jar were expected because of no changes in jar size during this phase. Interlimb coordination would be expected to be independent of object size for the healthy adults but not for the LCVA patients.

**Methods**

**Participants**

Fourteen patients with unilateral LCVA (mean age ± SD = 60.70 ± 10.00 years, 2 women and 12 men) and thirteen age-matched healthy adults (mean age ± SD = 59.14 ± 10.59 years, 5 women and 8 men) were recruited for the study. All of the participants were self-reported to be right-handed and signed informed consent forms. All patients were able to understand and respond to the directions given by the experimenter and demonstrated movements of the proximal and distal part of the impaired arm at Brunnstrom stage IV–VI (Brunnstrom, 1966). No patient showed excessive spasticity, defined as the modified Ashworth Spasticity Scale ≤ 2,
in any of the joints of the upper extremities (Bohannon, & Smith, 1987); deficits on sensory awareness of the affected limb, as measured by the Perception of Joint Position Sense Test (Leo, & Soderberg, 1981; mean score = 18); or apraxia according to the medical chart review. Patients had no history of previous stroke or visual deficit that would prevent participation. The time since stroke ranged from 6.6 to 84 months (mean = 31.23 months). The healthy controls had no previous history of neurological or psychiatric disease by self-report.

**Design**

This study used a counterbalanced, repeated-measures design. Participants were randomly assigned to one of two sequences: AB or BA, in which A and B represented the tasks of reaching to grasp the large target object and small object, respectively.

**Procedure**

During the experiment, each participant sat on a chair in front of the table and initially placed both arms on the switches located on the edge of the table, directly anterior to the shoulders. The trunk was secured to the chair back with a harness to prevent forward flexion. The target object was placed in line with the participant’s midsagittal plane. The target object was a jar with a cap of similar diameter to the jar. The jars were 7.5 (large jar) and 5 (small jar) cm in diameter. The weight and height of the large and small jars were the same. The distance of the object was corrected for each participant (80% arm length). Length of the arm was defined as the distance between the acromial end of the shoulder and ulnar head of the wrist. One third of the distance between the participant’s midline and the target location was the work position (Figure 1). All participants were instructed to reach

![Figure 1](image_url) — Experimental setup showing the participant’s initial position and movement execution process. The participant was instructed to reach to grasp the jar with the right/affected hand (phase I), put the jar on the work position (phase II), and reach to grasp and unscrew the jar cap with the left/unaffected hand (phase III).
and grasp a jar with the right/affected arm (phase I), put the jar on the work position (phase II), and unscrew the jar cap with the left/unaffected hand (phase III) at her or his preferred speed. Each participant performed three successful trials for each condition.

**Materials and Instrumentation**

A 6-camera motion-analysis system (VICON 370) was used in conjunction with a personal computer (an IBM clone) to capture the movement of the markers during reaching and grasping the jar and to collect two channels of analog signals simultaneously. Movements were recorded at 60 Hz and filtered by a low-pass, second-order Butterworth filter with forward and backward pass with a cut-off frequency of 5 Hz. Three markers were placed on each arm: on the radial styloid and medial aspect of the index finger and thumb. A reference marker was attached to the top of the cap and was used to determine the end of the reaching and grasping movement. The analog signals were collected from each hand switch and were used to determine the start of the movement. The VICON 370 system was used to track the kinematic data and to save the 3-D location of the markers together with analog data in a binary format.

For phases I and III, the start and the end of the movement were determined through the use of two switches and the reference marker on the jar. Before initiating movement, each of the participant’s hands rested on a switch. The beginning of movement for each hand was indicated separately so that the beginning of the right/affected hand movement was measured when that hand moved off the switch and the beginning of the left/unaffected hand movement was measured when that hand was lifted off the switch. The end of movement for each hand was also determined separately. It was the time when the distance between the reference marker on the top of the cap and the marker attached to the thumb of each hand was minimal. For phase II, movement beginning was indicated when the reference marker on the cap started to move, and movement end was determined when the velocity of the wrist dropped below 0.05 m/s.

**Data Reduction**

A customized LabVIEW analysis program was used. Analyses of intralimb performance and interlimb coordination were performed.

Analyses of intralimb performance included the reach and grasp components. The reach component was assessed based on the displacement of the marker on the wrist through space. The parameters included movement time (MT), total displacement (TD), and the percentage of MT in which peak velocity occurs (PPV). MT, a measure of temporal efficiency of movement, was defined to be the time between the start and end of movement. TD refers to the path of a hand in three-dimensional space during movement execution. TD is a measure of trajectory directness and indicates spatial control of reaching movement. Velocity was derived from displacement data. Normal reaching involves one acceleration phase and one deceleration phase of the velocity profile. The location of peak velocity changes with movement organization. A lower PPV implies a longer deceleration phase during which visually based correction of movement often occurs and implies less preplanning of the
reaching movements (Wu, Trombly, Lin, & Tickle-Degnen, 2000). As the size of object decreases, participants require a longer MT with a less direct trajectory (less TD) and longer time in the deceleration phase (lower PPV) to allow for accuracy to target (Marteniuk et al., 1990; Wu et al., 2000; Zoia et al., 2006). Because the task distance varied across participants, MT and TD were normalized to correct for variations in reaching distance.

The parameters of the grasp component included maximum grip aperture (MGA) and the percentage of the MT in which MGA occurred (PMGA). These were measured by the distance between the markers on the index finger and thumb tips. MGA was defined as the maximum distance between the two markers on these fingers. The size of the MGA is a function of the anticipated size of the object (Jeannerod, 1999) and is indicative of spatial control of grasp. We also calculated PMGA, indicating the temporal control of grasp. The time after MGA is for making corrections to the hand as it approaches the target. As the size of the object decreases, the participants adjust the timing of the hand by opening the aperture to a maximum at a progressively earlier time (lower PMGA; Marteniuk et al., 1990) and spend more time after MGA adjusting the precision of grasp.

Analysis of interlimb coordination included bimanual synchronization and temporal correlation of the hand movements at movement initiation and termination. Bimanual synchronization reflects the simultaneity of the actions of both hands (Wiesendanger et al., 1994) and includes onset synchronization and goal synchronization. To measure onset synchronization, the timing interval between the movement initiations of each hand was determined (Perrig et al., 1999; Serrien et al., 2001; Weiss et al., 2000; Wiesendanger et al., 1994). Goal achievement was set as the combined event of the jar put on the work position by the right/affected hand and grasping the cap by the left/unaffected hand. Temporal correlation refers to the degree of covariance of the hands (Weiss et al., 2000) and is determined by correlating the latency at movement onset for one hand with that for the other hand and by correlating the timing to finish the task between two hands (Perrig et al., 1999; Serrien et al., 2001; Weiss et al., 2000; Wiesendanger et al., 1994).

**Statistical Analysis**

Repeated-measures multivariate analyses of variance (MANOVAs), which control for the probability of type I error caused by the use of multiple tests of significance within the current study (Portney & Watkins, 2000), were used to examine the difference between the large- and small-jar conditions on movement kinematics. A repeated-measures MANOVA was conducted for reaching kinematics (i.e., MT, TD, and PPV) to evaluate object size as the within-subject factor. Follow-up univariate analysis of variance (ANOVA) for each dependent variable was used when the MANOVA demonstrated a significant effect. In the same way, repeated-measures MANOVAs were performed for dependent variables of grasping kinematics (i.e., MGA and PMGA) and bimanual synchronization (i.e., onset synchronization and goal synchronization) separately. Effect sizes were also calculated to indicate the magnitude of the effect. An effect of $r = .10$ represents a small effect, $r = .30$ a moderate effect, and $r = .50$ a large effect (Cohen, 1988).

Pearson’s correlation was used to evaluate the temporal correlation between the two hands. To test whether the temporal correlation was significantly different
between the large- and the small-jar conditions, we used the following formula (Rosenthal & Rubin, 1986).

\[
\frac{t_{\text{contrast}}}{\sqrt{(1 - \rho) \sum \lambda_i^2 + (1 - \rho^2) \sum \lambda_i^2 t_i^2 / 2df}}
\]

The \(t_i\) was calculated as

\[
t_i = \frac{r_i \sqrt{df}}{\sqrt{1 - r_i^2}}
\]

where \(r_i\) was the correlation coefficient and \(df\) was the degrees of freedom for the correlation. The \(\lambda_i\) was the weight we assigned to the importance of the \(i\)th correlation coefficient, and \(\rho\), which was defined as the intercorrelation among the variables, was zero in the current study (Rosenthal & Rubin, 1986). The alpha criterion was set at \(p = .05\) (one-tailed).

**Results**

The results are presented for the intralimb performance associated with the separate contribution of each hand followed by interlimb coordination of both hands.

**Intralimb Coordination**

Tables 1 and 2 display the descriptive and inferential statistics for the dependent variables for the healthy adults and the LCVA patients.

**Reaching to Grasp the Jar With the Right/Affected Hand (Phase I).** Contrary to our hypothesis, the repeated-measures MANOVA of the reach component revealed a nonsignificant main effect for object size for the healthy controls \(F(3, 10) = 1.17, p = .19\), but, as hypothesized, a significant main effect for object size was revealed in the LCVA patients \(F(3, 11) = 2.75, p = .047\). Post hoc ANOVAs revealed a significant and moderate to large effect on TD \((p = .005)\) but not on MT \((p = .09)\) and PPV \((p = .11)\) for the patients. Contrary to our hypothesis, the LCVA group tended to reach to grasp the small jar more directly than the large jar.

Regarding the kinematics of the grasp component, the repeated-measures MANOVA showed a significant main effect for object size for both the healthy adults \(F(2, 11) = 31.06, p < .001\) and the LCVA patients \(F(2, 12) = 49.67, p < .001\). Follow-up ANOVAs showed a significant and large effect of object size on MGA for both groups \((p < .001)\) as hypothesized. Consistent with our hypothesis, there was a significant and large effect of object size on PMGA for the healthy controls \((p = .001)\), but, inconsistent with our hypothesis, not on PMGA for the stroke patients \((p = .13)\). All participants used significantly larger hand apertures of the right/affected hand to the large jar than to the small jar. In addition, the control participants, but not the LCVA patients,
Table 1  Descriptive and Inferential Statistics for Intralimb Performance for the Healthy Adults

<table>
<thead>
<tr>
<th>Variable</th>
<th>Descriptive data (mean ± SD)</th>
<th>Univariate F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small jar</td>
<td>Large jar</td>
</tr>
<tr>
<td>Reaching to grasp the jar with the affected/right hand (phase I)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMT (s)</td>
<td>0.0033 ± 0.00053</td>
<td>0.0032 ± 0.00040</td>
</tr>
<tr>
<td>NTD</td>
<td>1.12 ± 0.035</td>
<td>1.11 ± 0.032</td>
</tr>
<tr>
<td>PPV</td>
<td>47.49 ± 6.25</td>
<td>50.41 ± 5.22</td>
</tr>
<tr>
<td>MGA (mm)</td>
<td>103.66 ± 12.62</td>
<td>127.06 ± 9.06</td>
</tr>
<tr>
<td>PMGA</td>
<td>66.92 ± 12.93</td>
<td>81.30 ± 10.30</td>
</tr>
<tr>
<td>Moving the jar to midline with the affected/right hand (phase II)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMT (s)</td>
<td>0.0040 ± 0.0010</td>
<td>0.0043 ± 0.0013</td>
</tr>
<tr>
<td>NTD</td>
<td>1.10 ± 0.043</td>
<td>1.11 ± 0.073</td>
</tr>
<tr>
<td>PPV</td>
<td>44.97 ± 5.92</td>
<td>45.88 ± 7.30</td>
</tr>
<tr>
<td>Reaching to grasp the jar and opening the cap with the unaffected/left hand (phase III)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMT (s)</td>
<td>0.0083 ± 0.0025</td>
<td>0.0084 ± 0.0033</td>
</tr>
<tr>
<td>NTD</td>
<td>1.27 ± 0.16</td>
<td>1.26 ± 0.12</td>
</tr>
<tr>
<td>PPV</td>
<td>43.49 ± 10.65</td>
<td>46.71 ± 14.21</td>
</tr>
<tr>
<td>MGA (mm)</td>
<td>97.56 ± 8.88a</td>
<td>110.20 ± 10.27a</td>
</tr>
<tr>
<td>PMGA</td>
<td>64.46 ± 21.72a</td>
<td>65.31 ± 20.74a</td>
</tr>
</tbody>
</table>

Abbreviations: NMT, normalized movement time; NTD, normalized total displacement; PPV, percentage of movement time in which peak velocity occurs; MGA, maximum grip aperture; PMGA, percentage of movement time in which MGA occurs.

$a$ $n = 12$ because of missing data from one of the subjects.

achieved MGA significantly earlier when reaching for the small jar than when reaching for the large jar.

**Moving the Jar to Midline With the Right/Affected Hand (Phase II).** As hypothesized, the repeated-measures MANOVA for reaching kinematics showed no significant main effect in either group [healthy adults: $F(3, 10) = .93, p = .23$; LCV A patients: $F(3, 11) = .41, p = .37$].

**Reaching to Grasp the Jar and Opening the Cap With the Left/Unaffected Hand (Phase III).** The repeated-measures MANOVA revealed a nonsignificant main effect of object size on reaching kinematics for the healthy controls [$F(3, 10) = .51, p = .34$] and the LCV A patients [$F(3, 11) = .19, p = .45$]. However, repeated-
The MANOVA for the grasping kinematics showed a significant main effect for the controls \([F(2, 10) = 7.80, p = .0045]\) and the patients \([F(2, 12) = 13.74, p = .001]\). Post hoc ANOVAs revealed a significant and large effect on MGA for the healthy adults \((p = .002)\) and LCV A patients \((p = .007)\) but not on PMGA for either group \((p = .46 \text{ for the healthy adults and } p = .06 \text{ for the patients})\).

Table 2 Descriptive and Inferential Statistics for Intralimb Performance for the Left Cerebral Vascular Accidents Patients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Small jar</th>
<th>Large jar</th>
<th>(F(1, 13))</th>
<th>(p)</th>
<th>(r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaching to grasp the jar with the affected/right hand (phase I)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMT (s)</td>
<td>0.0039 ± 0.00086</td>
<td>0.0041 ± 0.00095</td>
<td>1.92</td>
<td>.09</td>
<td>.36</td>
</tr>
<tr>
<td>NTD</td>
<td>1.16 ± 0.11</td>
<td>1.20 ± 0.12</td>
<td>9.17</td>
<td>.005</td>
<td>.64</td>
</tr>
<tr>
<td>PPV</td>
<td>48.56 ± 6.06</td>
<td>45.31 ± 7.17</td>
<td>1.65</td>
<td>.11</td>
<td>.33</td>
</tr>
<tr>
<td>MGA (mm)</td>
<td>108.26 ± 10.18</td>
<td>127.92 ± 9.23</td>
<td>101.87</td>
<td>&lt;.001</td>
<td>.94</td>
</tr>
<tr>
<td>PMGA</td>
<td>71.76 ± 18.36</td>
<td>78.11 ± 10.10</td>
<td>1.39</td>
<td>.13</td>
<td>.31</td>
</tr>
<tr>
<td>Moving the jar to midline with the right/affected hand (phase II)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMT (s)</td>
<td>0.0048 ± 0.0012</td>
<td>0.0047 ± 0.0011</td>
<td>0.19</td>
<td>.34</td>
<td>.12</td>
</tr>
<tr>
<td>NTD</td>
<td>1.18 ± 0.19</td>
<td>1.17 ± 0.19</td>
<td>1.04</td>
<td>.17</td>
<td>.27</td>
</tr>
<tr>
<td>PPV</td>
<td>43.78 ± 7.47</td>
<td>45.31 ± 6.47</td>
<td>0.89</td>
<td>.18</td>
<td>.25</td>
</tr>
<tr>
<td>Reaching to grasp the jar and opening the cap with the unaffected/left hand (phase III)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMT (s)</td>
<td>0.0061 ± 0.0010</td>
<td>0.0063 ± 0.0018</td>
<td>0.37</td>
<td>.28</td>
<td>.17</td>
</tr>
<tr>
<td>NTD</td>
<td>1.19 ± 0.080</td>
<td>1.19 ± 0.11</td>
<td>0.14</td>
<td>.36</td>
<td>.10</td>
</tr>
<tr>
<td>PPV</td>
<td>49.19 ± 7.83</td>
<td>48.66 ± 8.67</td>
<td>0.081</td>
<td>.39</td>
<td>.077</td>
</tr>
<tr>
<td>MGA (mm)</td>
<td>101.34 ± 14.73</td>
<td>108.99 ± 9.07</td>
<td>8.30</td>
<td>.007</td>
<td>.62</td>
</tr>
<tr>
<td>PMGA</td>
<td>47.93 ± 26.22</td>
<td>57.68 ± 24.72</td>
<td>2.80</td>
<td>.06</td>
<td>.42</td>
</tr>
</tbody>
</table>

Abbreviations: NMT, normalized movement time; NTD, normalized total displacement; PPV, percentage of movement time in which peak velocity occurs; MGA, maximum grip aperture; PMGA, percentage of movement time in which MGA occurs.

**Interlimb Coordination**

The descriptive statistics for bimanual synchronization in the healthy adults and the LCVA patients are shown in Table 3. The MANOVA revealed a nonsignificant main effect for bimanual synchronization in both the healthy adults \([F(2, 11) = 1.16, p = .18]\) and the LCVA patients \([F(2, 12) = 1.07, p = .19]\). The results indicated that bimanual synchronization was independent of object size for both groups as hypothesized.
In terms of the temporal correlation, Figure 2 illustrates the correlation coefficients between the two hands at movement initiation and movement termination for each object-size condition in each group. The contrasts in the correlation coefficient between the different object sizes were not significant for movement initiation (control: $t_{\text{contrast}} = .50$, $p > .05$; LCV A: $t_{\text{contrast}} = 1.19$, $p > .05$) and movement
termination (control: $t_{\text{contrast}} = .48, p > .05$; LCVA: $t_{\text{contrast}} = .55, p > .05$) for either group. These results indicate that the LCVA patients preserved temporal correlation during movement initiation and termination, just as the healthy adults did.

**Discussion**

This study presents an investigation of intralimb and interlimb coordination between different object sizes when each hand performed different actions simultaneously (reaching to grasp a jar and also opening the jar cap). The findings partially support the hypothesis and suggest that both healthy adults and LCVA patients adapt the grasp component but only the LCVA patients change the reaching activity according to object size. These findings confirm the notion of the visuomotor channel model (Jeannerod, 1999) in which task constraint has an influence on the reach and grasp components and generalize this notion from unimanual prehension tasks to functional and asymmetrical bimanual prehensile movements. However, the influence of object size on reach component was only observed in the LCVA patients, not in the healthy adults. In addition, the bimanual coordination is independent of the change in object size in the healthy adults, which was consistent with the hypothesis, but not in the LCVA patients, which was inconsistent with the hypothesis.

**Intralimb Coordination**

**Performance of the Individual Hand in Phase I.** The results revealed that the kinematic variables of the reach component were not influenced by object size for the healthy adults. The results for the healthy adults were inconsistent with the findings of previous studies (Bootsma et al., 1994; Kudoh et al., 1997; Marteniuk et al., 1990; Zoia et al., 2006) in which longer MT and lower PPV were found in tasks with smaller objects (e.g., 1–3 cm in diameter or length) than larger objects (e.g., 8–10 cm in diameter or length). The inconsistent findings can be explained in part by the object size used in our study compared with the previous studies. The precision requirements of both the large and small objects in the current study were low, and the difference in the accuracy demand between these two objects was not large enough to influence the reach component. However, the small object, for example, a jar 1 cm in diameter, might not be ecologically relevant, not often seen in daily life, and, thus, not be appropriate for use in this study.

In contrast to the reaching performance of the healthy adults, the LCVA patients moved the affected arm more directly (less normalized TD) when reaching toward the small jar than the large jar. Patients might encounter greater difficulty in extending fingers to grasp large objects than to grasp small objects because of flexor synergy or weakness of the extensor muscle (Carr & Shepherd, 2003). The task with a small object might be easier for patients to execute. The easier task for grasping should also be easier for reaching in terms of interaction between the two components, resulting in effective spatial control (direct movement trajectory) of reaching.

The object size had an impact on the grasping performance of the right hand in phase I for the healthy adults; hand opening (MGA) was larger and the maximum opening of the hand occurred later (greater PMGA) when reaching to grasp the large jar than the small jar. The results for the grasp component in healthy adults
are consistent with the findings of previous studies (Cope & Trombly, 1998; Kudoh et al., 1997; Marteniuk et al., 1990; Mon-Williams & Tresilian, 2001; Säfström & Edin, 2005; Zoia et al., 2006) and also concur with the notion proposed by Jeannerod’s visuomotor channel model (Jeannerod, 1999); the intrinsic properties of the object (e.g., size) led to the proportional sizing of the hand to that of the object and required more time to scale the hand aperture to the actual size of the object. As was the case for unimanual movement, the healthy adults were able to combine visual information about the object size with previous experience to form a visual representation that allowed them to preshape the size of hand aperture in advance so as to appropriately grasp the jar during a bimanual task (Berryman, Yau, & Hsiao, 2006; Jeannerod, 1999).

For LCVA patients, there were significant effects on MGA but not on PMGA, although the means were in the hypothesized direction. These findings suggest that the LCVA patients preserved the flexibility needed for adjusting the hand opening based on object size but had incurred deficits in the temporal control of the grasp component required to accomplish different task requirements during bimanual movements.

**Performance of the Individual Hand in Phase II.** When moving the jar toward the body with the right/affected hand, there were no significant effects of object size on movement performance for either group. This might be because of the fact that the similar movement patterns in this phase did not involve changes in object size. Accordingly, there was no need for movement adjustment to object size. Accordingly, there was no need for movement adjustment to object size.

**Performance of the Individual Hand in Phase III.** When reaching to grasp the jar with the left/unaffected hand, there were no significant effects of object size on the reach and grasp components, except for the variable of MGA in both groups. Both groups used similar reaching styles and temporal control of grasping (PMGA) regardless of the object size and adjusted the spatial aspect of the grasp component (MGA) to the change of object size to successfully achieve the task goal. The results indicated that the LCVA patients preserved motor control of the unaffected hand during bimanual movement just as the healthy adults did. It is noteworthy that, for the healthy adults, the effect on PMGA in phase III was different from that in phase I, in which the PMGA was less with the small jar than with the large jar. One possible reason is that the left hand, used in phase III, can use the information on the temporal control of grasping and sensory feedback used by the right hand in phase I (Cunningham, Stoykov, & Walter, 2002; Perrig et al., 1999). With the experience of grasping from the right hand, participants might preplan for reaching to grasp the small object well with less on-line error correction and can use the same temporal planning as in the large-jar condition. A similar PMGA for both tasks in phase III was perhaps thus obtained.

**Interlimb Coordination**

Object size did not significantly influence the bimanual synchronization and temporal correlation of the hands at the start and the end of movement in either group. The robust principle of goal invariance (Perrig et al., 1999) was further evidenced by the findings of nonsignificant effects of object size on bimanual coordination at the end of movement for both the healthy and the LCVA participants. This finding
suggests a higher-order control system in which a common temporal mechanism is used to anticipate the limb’s work positions and which organizes each component of the limbs into a single unit, even under different constraints, so as to ensure bimanual coordination at the common goal (opening the jar cap; Jackson et al., 1999; Perrig et al., 1999; Serrien & Wiesendanger, 2000). The existence of goal invariance in the LCVA patients suggests that the control mechanism for temporal coordination of both hands is well-preserved following stroke (Rice & Newell, 2004). The results of interlimb coordination in the LCVA patients are not compatible with that of Utley et al. (2004). This is possibly because the large object used in the Utley et al. study (2004) was too large for the children with cerebral palsy to grasp bimanually (2 out of 8 children failed to execute), and the excessive challenge of the grasping task resulted in a disruption of bimanual coordination. Another possibility is that patients with cerebral palsy and with stroke might have different ways to respond to object size.

In summary, the LCVA participants, using the affected hand, reached more directly toward a small object than toward a large object. The LCVA participants revealed deficits in temporal control of grasping with the affected hand but preserved control of the unaffected hand and bimanual coordination. The clinical implication is that the functional bimanual tasks using a small object as task target might be easier for LCVA patients to perform because of less requirements of voluntary extension of the fingers. The temporal control of grasping with the affected hand needs to be improved and might be trained by practicing a variety of functional bimanual prehension tasks with varying sizes of objects.

Although the range of onset time after stroke in the LCVA patients employed in this study was wide, it is evident that the major influence on the performance of bimanual tasks in stroke patients is the severity of effect on motor function. Onset time might not play an important role during bimanual movement (Harris-Love, Waller, & Whitall, 2005; Rice & Newell, 2004), and the degree of bimanual coordination to the change of object size might not be directly influenced by the onset time. Because motor status was similar across these patients in the study (Brunnstrom stage IV–VI), the variability of onset time might not threaten the internal validity. Future research might employ patients with right CVA with a wide array of object sizes or a variety of object shapes during various asymmetrical bimanual tasks to further understand how task object induces different behavioral adaptations to different properties of the task object in patients with LCVA and right CVA.

**Conclusion**

This study provides evidence on behavioral adaptations of bimanual movement performed under conditions of different sizes of task objects in patients with LCVA and healthy adults and extends the notion of the visuomotor channel model to bimanual tasks. The strongest evidence supporting the visuomotor channel model came from the spatial control of grasping: the MGA covaried with object size for both hands in both groups. This study also confirms the robust principle of temporal synchronization regardless of the specific task constraints, suggesting the existence of a common temporal mechanism, at a higher order of control in the system, for synchronizing the separate channels of both hands to the end goal. In
contrast with the performance by healthy adults, stroke patients exhibited spatial adaptation of reaching to the object size and deficits in temporal adaptation of grasping to object sizes in the affected hand. However, stroke patients preserved the capacity for grasping adaptation in the unaffected hand and bimanual coordination to the object size just as the healthy adults did. Incorporation of various sizes of objects during the bimanual task in clinical interventions might help improve the temporal control of the affected hand. Future research will investigate how various object properties during different types of asymmetrical bimanual tasks influence intralimb and interlimb performance.

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References


